

# **Laser Produced Plasma EUV Sources for Device Development and HVM**

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## **ABSTRACT**

Laser produced plasma (LPP) systems have been developed as the primary approach for the EUV scanner light source for optical imaging of circuit features at sub-22nm and beyond nodes on the ITRS roadmap. This paper provides a review of development progress and productization status for LPP extreme-ultra-violet (EUV) sources with performance goals targeted to meet specific requirements from leading scanner manufacturers. We present the latest results on exposure power generation, stable collection, and clean transmission of EUV through the intermediate focus. Semiconductor industry standards for reliability and source availability data are provided. We report on measurements taken using a 5sr normal incidence collector on a production system. The lifetime of the collector mirror is a critical parameter in the development of extreme ultra-violet LPP lithography sources. Deposition of target material as well as sputtering or implantation of incident particles can reduce the reflectivity of the mirror coating during exposure. Debris mitigation techniques are used to inhibit damage from occurring, the protection results of these techniques will be shown over multi-100's of hours.

**Keywords:** EUV source, EUV lithography, Laser Produced Plasma, Collector, Droplet Generator

## **1. INTRODUCTION**

EUV Lithography is the front runner for next generation critical dimension imaging after 193 nm immersion lithography for critical layer patterning below the 22 nm node. Leading device manufacturers took delivery of first generation EUV sources in 2011 and are ramping those tools to pilot-line capability in 2012. In the technology development the capability of high power EUV sources remains a high risk and is ranked as critical along with other technologies such as resist and mask, requiring significant improvements to enable the realization of EUV lithography in high volume. High

sensitivity photoresists with good line-edge-roughness (LER) and line-width-roughness (LWR) are needed to keep the required source power within reasonable limits. Photoresist sensitivity and overall optical transmission through the EUV scanner are the basis to derive EUV source power requirements within the usable bandwidth of 2 %. Scanner manufacturers are requiring clean EUV power of 250W at the intermediate focus (IF) to enable > 100 wph scanner throughput assuming photoresist sensitivities at levels of 15 mJ/cm<sup>2</sup>.

LPP EUV lithography light sources generate the required 13.5 nm radiation by focusing a 10.6 micron wavelength CO<sub>2</sub> laser beam onto tin (Sn) targets creating highly ionized plasmas with electron temperatures of several 10's of eV<sup>1-4</sup>. EUV photons are radiated isotropically by these ions. Photons are collected with a temperature-controlled graded multilayer coated normal-incidence mirror (collector), and focused to an intermediate point from where they are relayed to the scanner optics and ultimately to the wafer. High conversion efficiency (CE) of the laser energy into EUV energy is critical to meeting the required power levels. The collector is protected from the plasma by a debris mitigation technology based on a hydrogen buffer gas. High-energy ions, fast neutrals, and residual source element particles are mitigated to maintain the reflectivity of the collector mirror and enable a long lifetime of this component. Diagnostics measuring the properties of emitted light at both the plasma and IF are used to characterize the output of the source.<sup>5</sup>

A total of eight HVM I sources have been built and are operational. Five of these sources are now installed at chipmaker R&D facilities and are being used to expose wafers for device production, two are used at Cymer in San Diego for development of upgrades and one is being used by a leading scanner manufacturer for continued development of the scanner modules. Collector lifetime in the field now exceeds 30 billion pulses principally due to the development of new coatings. The source availability as defined by SEMI E10 reached 70% in the fourth quarter of 2011, up from ~50% in the prior quarters. The increase in source availability is primarily due to the increase in lifetime of two critical modules; the collector and the droplet generator. Cymer has deployed service teams to support source operation, 7 days per week, 24 hours per day, in all locations where the sources are installed, which now includes Korea, Taiwan, Japan, USA and Europe. Our efforts in 2011 were focused on building, shipping and installing sources at our customer's facilities. With that work now being complete for HVM I, we have increased our focus to using the sources in our factory to develop and test power upgrades and availability enhancements. A third HVM I source is being built and will augment the other two in San Diego to allow us to increase the test time for these purposes. Each upgrade has a dedicated test source and test team to accelerate the qualification and ultimate release of each power upgrade on our roadmap. In these proceedings we show results from testing of the upgrade configurations and operating modes including: 20 W average power with closed-loop active dose control meeting the requirement in upgrade 1 configuration, 32 W average power with closed-loop active dose control meeting the requirement in upgrade 2a configuration, and 50 W raw average power when using our pre-pulse technology. In 2012 Cymer is building the first HVM II sources for shipment to our customers and to be

used in San Diego as test sources. We have upgraded our LT1 development source<sup>6</sup> to include several of the new critical technologies to be included in HVM II. Test results from LT1 using a higher power CO<sub>2</sub> laser configuration and a pre-pulse have already shown up to 160 W in-burst EUV power at low duty cycle, and drive laser power has been measured up to 28 kW peak power during the burst.

## 2. LPP SOURCE SYSTEM

The system architecture is shown in a scale drawing in Figure 1. The three major subsystems of the source are the drive laser, the beam transport system (BTS) and the source vessel. The drive laser is a CO<sub>2</sub> laser with multiple stages of amplification to reach the required power level of up to ~30 kW.<sup>7,8</sup> It is operated in pulsed mode at ~50 kHz with radio-frequency (RF) pumping from generators (not shown) operating at 13.56 MHz. The laser is typically installed in the sub-fab along with its RF generators and water-to-water heat exchangers. The laser beam is expanded as it leaves the drive laser to lower the energy density on the BTS mirrors and allows higher NA for focusing the beam to small spot size. Three turning mirrors are used to allow the beam to travel from the sub-fab to the fab through the waffle-slab floor with the needed flexibility for positioning the laser with respect to the source vessel (and scanner) on the floor above. The laser and BTS are completely enclosed and interlocked to meet laser class 1 requirements. The BTS delivers the beam to a focusing optic where the light at 10.6 mm wavelength is focused to a minimum spot size defined by the numerical aperture of the focusing system. The converging beam propagates through a central aperture in the collector and strikes the droplet at the focus of the ellipsoidal collector mirror inside the vacuum space of the source vessel. The droplet generator delivers liquid tin droplets of 30 mm diameter to the same position at ~50 kHz repetition rate; both laser pulse and droplets are steered and timed to ensure proper targeting. The laser pulse vaporizes and heats the tin into a plasma cloud of critical temperature and density. The EUV light emitted by the plasma is collected and reflected with the multilayer-coated ellipsoidal mirror to the IF where it passes through a small aperture into the scanner volume that houses the illumination optics.

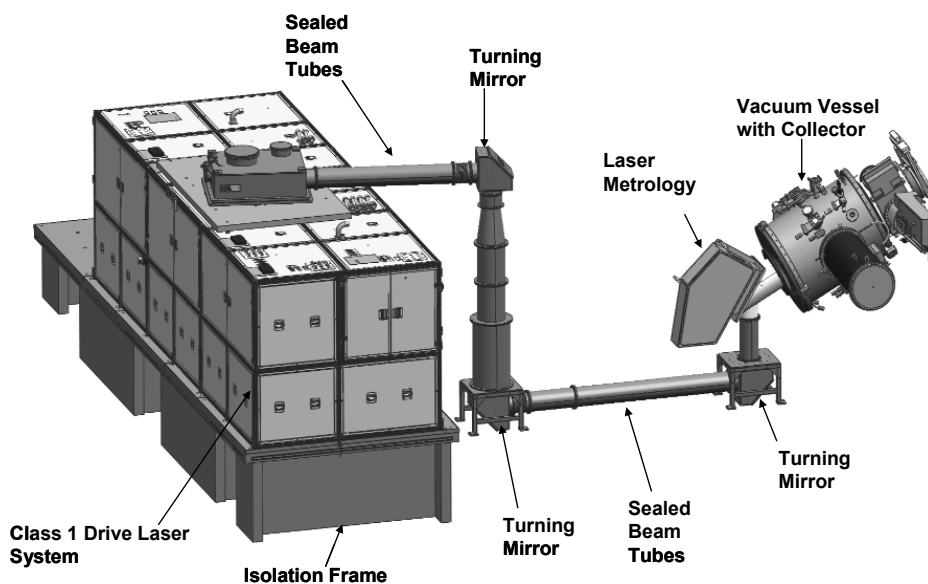


Figure 1: Scale Drawing of Laser Produced Plasma Source.

To ensure that no contamination can reach the scanner volume an IF protection module surrounds the aperture and suppresses flow and diffusion<sup>9</sup>. Other modules on the source vessel include the droplet catcher which collects the unused droplets between the bursts, and metrology modules used to measure EUV energy and to image droplets and plasma. The source controller turns on and off bursts of pulses as commanded by the scanner, which can be as long as several seconds. Exposures at full source power correspond to typically several hundred milliseconds for a 26 x 33mm field size using 15 – 20 mJ/cm<sup>2</sup> resist. The ratio of time when the burst is on to the period between bursts defines the intra-field duty cycle.

### 3. RECENT DEVELOPMENT RESULTS

Results of testing in San Diego on our internal test source Pilot 8 were used to qualify our upgrade 1 performance at 20W average power. During this test the source was being driven by a scanner simulator which mimics the actual operation of the source during wafer exposures in a fab. This allows us to post-process the results and evaluate many parameters including dose stability by individual die as shown in Figure 2. Each die has better than the required  $\pm 0.5\%$   $3\sigma$  dose stability as shown in the wafer maps. These are just two of over 1000 wafers simulations run as part of the qualification. The test concluded with more than 99.7% of the dies on all wafer simulations meeting dose stability requirements and allowed qualification of the upgrade and its release to the field.

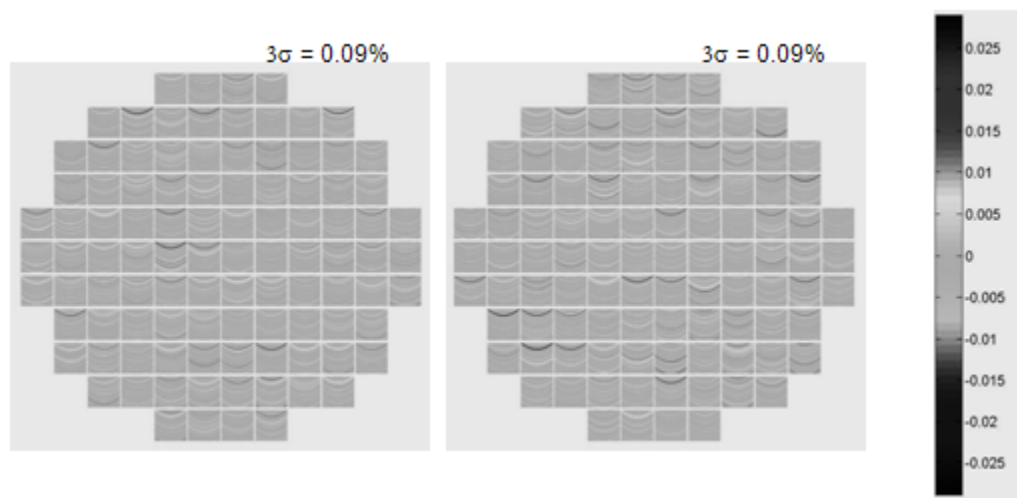
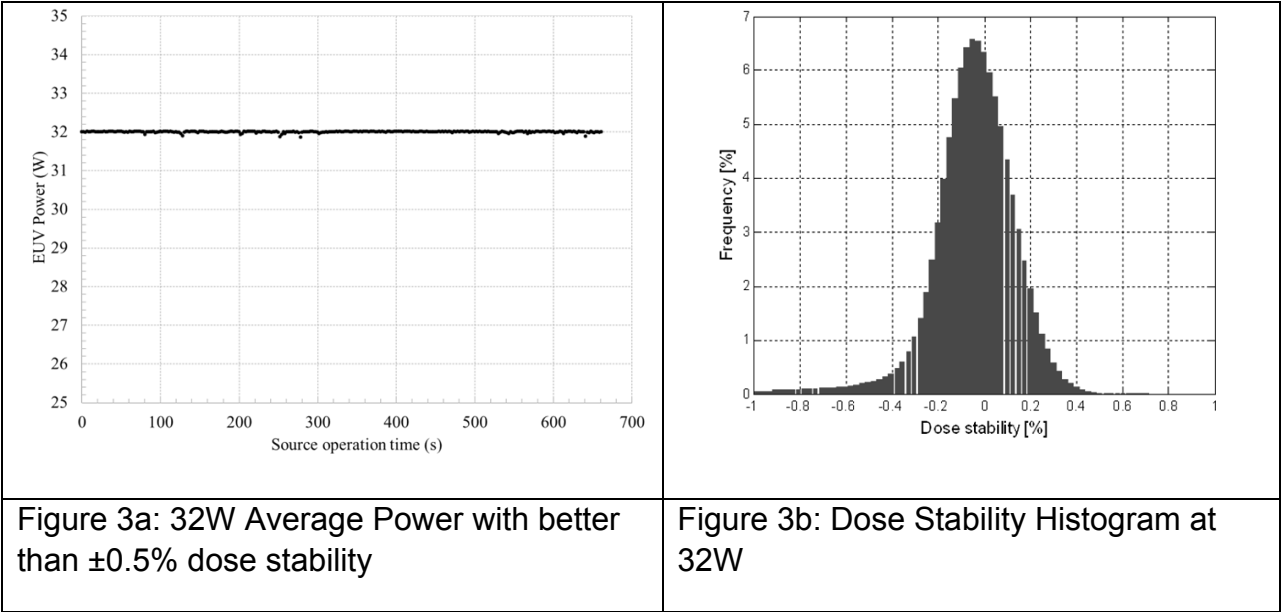


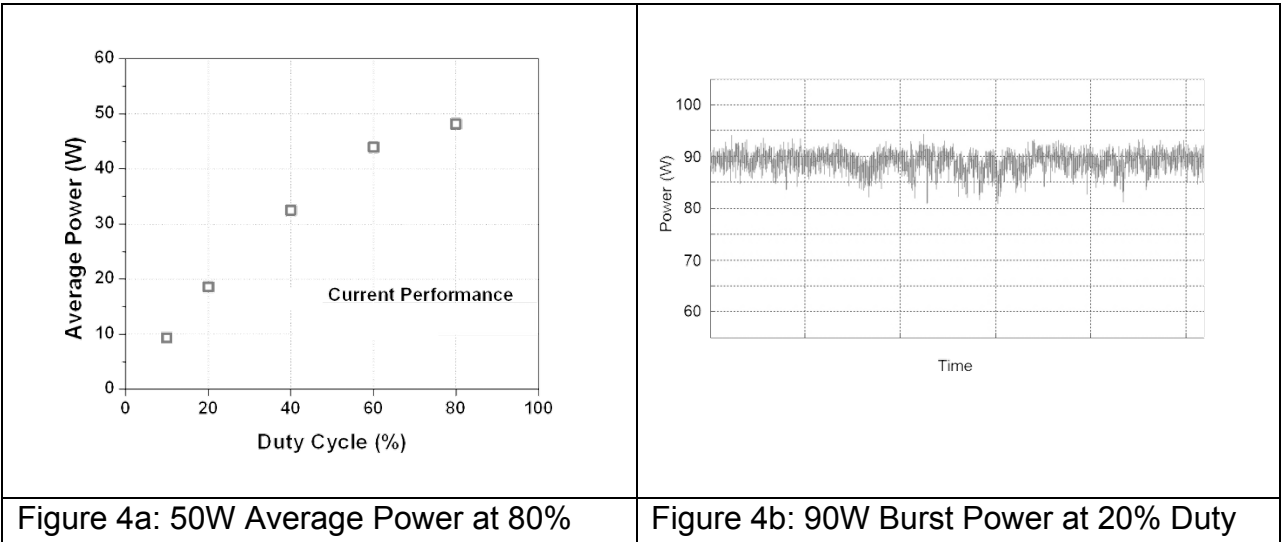
Figure 2: 20W Average Power Dose Stability Die to Die

Tests from our internal test source Pilot 7 are shown in Figures 3a and 3b. This test configuration included upgrades to the drive laser which allows continuous operation of the source during the full die scan and operation at high duty cycle. 32W average

power with better than  $\pm 0.5\%$   $3\sigma$  dose stability is shown. During this test the source was running at 92% duty cycle with a burst duration of 2 seconds.



The Pilot 7 test source also has the pre-pulse module integrated into the configuration. The pre-pulse functionality is capable of the full repetition rate of the source of 50kHz. We have been testing the pre-pulse operation on this source for about four months and have achieved our record average power results just recently. Over a period of days we conducted testing through the full range of duty cycles. By incrementally increasing burst duration while maintaining a constant period between bursts, we increased the duty cycle up to 80% where the source was operated at an average EUV power of ~50W (Figure 4a).



Duty Cycle using Pre-pulse	Cycle (18W average power) using Pre-pulse
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At 20% duty cycle the power in the burst was ~90W (open-loop operation) by using the pre-pulse technology, as shown in Figure 4b. This corresponds to 18W average power; however, is important to show the capability of the source to create levels very close to the final 100W power target, which is expected to be completed by the end of the year.

#### 4. AVAILABILITY

In the fourth quarter of 2011 the source availability according to SEMI E10 monitoring increased to 70%, up from 50% in prior quarters, as shown in Figure 5. This increase was primarily due to the achieved increased lifetime of two major modules of the source, the collector and the droplet generator. Also influencing the source availability improvement was automation in the software and improved controls to minimize operator intervention. The data shown is the 13-week-average of the five sources at chipmaker sites in 2011.

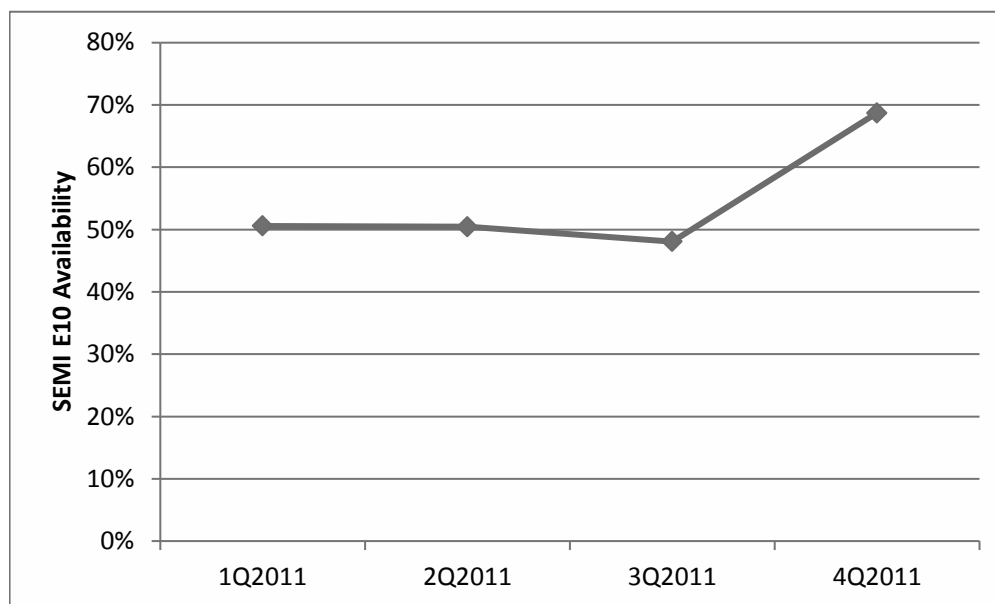


Figure 5: Source Availability in 2011 (SEMI E10)

Significant advancements in collector lifetime were made in 2011, as shown in Figure 6. This improvement is primarily due to the coatings used on the surface of the collector substrate and their resistance to reflectivity degradation. The dark circles were the results of our original life test completed in 2010 and shown at SPIE 2011<sup>4</sup>. The results of two new coatings on collectors installed on sources at chipmakers show the current performance and their associated significant lifetime improvement. Based on these data we can state with confidence that we have achieved our 30 billion pulse lifetime

milestone and are now testing 'new coating 2' to its limit, expecting it to meet the next milestone of 60 billion pulses lifetime. 60 billion pulses will allow for a full quarter of a year of collector lifetime under pilot-line operation modes. Continued advancement of coatings and debris mitigation techniques are expected to enable further increases of the collector lifetime to meet the ultimate goal of one year.

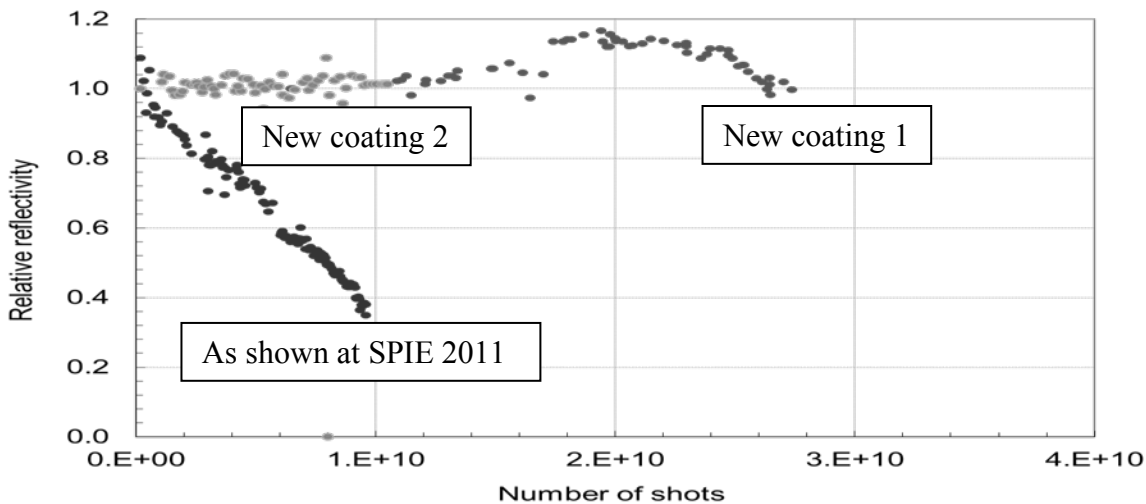
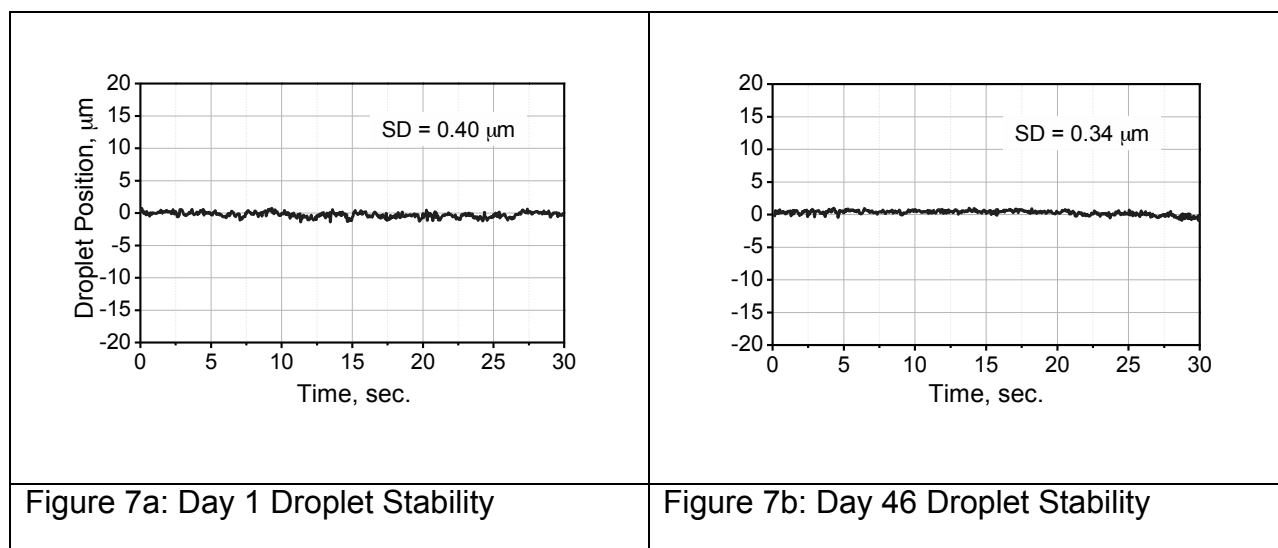


Figure 6: Recent Collector Lifetime Result for Sources in the Field

Extending the lifetime of the droplet generator is a major focus of our development at Cymer. Reliability improvements in 2011 were significant and have allowed us to now consider modes of operation that use the components for much longer period of time, rather than replacing them frequently. Still, today in the field the maximum usage time is about one week, as it is limited by the volume of tin stored in the generator reservoir. The generator reaches this lifetime only if no component failures occur. By eliminating the failure modes and increasing the size of the reservoir, or by refilling it in-situ, the run time of this critical module can be increased. Data from testing a droplet generator on a test stand at Cymer over a period of 46 days are shown in Figure 7. These results show the capability of the component to run for this extended period of time and not to deteriorate or lose stability. This new mode of operation is also being used on our internal sources where we have recently achieved 800 hours of droplet generator operation while producing EUV light.





## 5. ROADMAP

The EUV Power is calculated by taking the EUV power emitted into  $2\pi$ , multiplying by the collection efficiency and subtracting the losses due to dose control overhead and transmission. For current HVM I sources these parameters are estimated in the roadmap shown in Figure 9. For HVM II the goal for clean EUV power is 250 W. A scalable EUV source architecture is needed to enable the evolution of EUV lithography during the life cycle of the technology. Laser-produced-plasma (LPP) sources are expected to deliver the necessary power for critical-dimension high-volume manufacturing (HVM) scanners for the production of integrated circuits in the post-193 nm immersion lithography era.

EUV Source Power Roadmap			
Source Model	HVM I	HVM II	HVM III
Average Laser Power (kW)	13	29	31
In-band CE (%)	3.0	3.5	4.0
<b>Clean EUV Power (W)</b>	<b>105</b>	<b>250</b>	<b>350</b>

Figure 9: Projected LPP EUV Source Roadmap

## 6. SUMMARY

Laser-produced plasmas have been shown to be the leading source technology with scalability to meet requirements from leading scanner manufacturers and provide a path toward higher power as the lithography tools evolve over their life cycle. Eight HVM I LPP sources have been built by now and are operational around the world. An average power of 50W at intermediate focus at 80% duty cycle using pre-pulse technology has

been reported. The capability of meeting the dose stability target of  $\leq \pm 0.2\%$   $3\sigma$  has been demonstrated. Normal-incidence collector mirrors with  $> 5$  sr light collection and high average reflectivity are being produced in volume and are lasting for long lifetimes in production HVM I sources. The combination of 10.6  $\mu\text{m}$  laser light and Sn droplet source element is proving to provide reliable operation, with the sources in the field having now reached 70% availability. HVM II sources are being built, and their integration will begin in this year's second quarter. Several sources will be built for use as internal test sources and for shipment to ASML and chipmakers later in the year.

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